Large Scale Forcing and Oceanic Response

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LONG-TERM GOALS

The long-term goal is to observe, understand, and model air-sea interaction, upper ocean variability, and links between the upper ocean and the interior over a wide range of environmental conditions.

OBJECTIVES

The goal of the work in the eastern North Atlantic done as part of the Subduction Experiment is to observe the structure and dynamics of the Ekman layer and learn how, over an area such as the eastern end of the Bermuda-Azores high pressure cell, the convergence of the Ekman layer carries water from the surface into the main thermocline. The objectives of the observational component have been to: 1) make high quality, direct observations at widely spaced surface moorings in the Subduction and ASTEX (Atlantic Stratocumulus Transition Experiment) region of the surface forcing (wind stress and buoyancy flux) fields; 2) observe the oceanic velocities and temperatures at these sites, resolving the vertical structure of the upper ocean and its temporal variability over two annual cycles; 3) collect sufficient information about the surface forcing and upper ocean structure at sites between the moorings to allow extrapolation over the whole Subduction region of the description of the mixed layer response to atmospheric forcing; 4) observe at a site central to Subduction the response of the thermocline and the interior of the ocean as well as of the mixed layer. The objectives of modeling done in conjunction with the analysis of the data are to gain further understanding of how materials and properties are transferred from the mixed layer into the ocean interior in regions of Ekman convergence, of the role of large scale variations in atmospheric forcing in subduction, and of vertical transfers in strong frontal regions.

APPROACH

The approach has been to combine analysis of data collected during the Subduction experiment with modeling. The observational objectives were met by equipping each of five moorings deployed in a large square array, spanning 18° to 33°N and 22° to 33°W, with a fifth mooring in the center, with meteorological and oceanographic instrumentation, by carrying out shipboard observations during the mooring cruises, and by obtaining additional data sets to bolster the spatial and temporal coverage. The moored array work was done jointly with Russ Davis of SIO (Scripps Institution of Oceanography). The additional data collected included ship of opportunity XBTs and gridded fields from numerical weather prediction models and climatological data bases. Scientific analysis of the moored array data set started with analysis of the atmospheric forcing data from the array in the context of climatological data and gridded fields from the European Centre for Medium Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) and development of a gridded data set descriptive of the surface forcing during Subduction. The response of the upper ocean to local forcing at each of the five sites was then examined, and the temporal evolution of the upper ocean at each of the five sites characterized. The local forced response at each site was contrasted with predictions of various mixed layer models, including PWP. The understanding of the forced response is being combined with the gridded forcing fields to produce a two year description of the forced response of the upper ocean over the whole Subduction region. This is contrasted with climatological upper ocean temporal variability and horizontal and vertical structure and with the response to climatologically typical forcing inferred from our understanding of the forced response. Finally, the surface forcing and upper ocean fields are being used to quantify subduction rates and the various contributions to the subduction process.

In the modeling component, a basin-scale, non-eddy resolving, primitive equation model is used to study the large-scale processes that transfer materials and properties from the mixed layer into the main thermocline. The model includes parameterizations of turbulent mixing in the near surface layer and tracer transport processes by mesoscale eddies. Atmospheric forcing fields for approximately 10 years preceding and extending through the time periods of the Subduction Experiment have been derived from the NCEP reanalyses and the ECMWF atmospheric weather prediction model. Direct comparisons will be made between the simulated and observed fields in the Subdudction region. Issues relating to subduction at fronts have been investigated with a series of high resolution primitive equation models. Analysis with potential vorticity, passive tracers, and simulated floats is used to study higher order processes such as cross frontal exchange, subduction, eddy formation, and mixing. The influences of large scale deformation fields on the maintenance, stability, and mean frontal structure are also being investigated.

WORK COMPLETED

Gridded forcing fields (ECMWF, NCEP) and climatological data sets were obtained and compared with the buoy data. Based on these comparisons, gridded surface meteorological and air-sea flux data sets have been prepared at 1 hour and 1° latitude/longitude resolution and written to CD-ROM (Moyer and Weller, 1997). The mooring data has been analyzed, to local response isolated, and comparisons done with one-dimensional upper ocean models. The mooring data was supplemented with XBT and CTD data to develop a description of the upper ocean variability over the Subduction region (10°-40°N, 10°-40°W) with monthly resolution both for June 1991-July 1993 and as a climatological average. These fields are used to evaluate spatial gradients of mixed layer depth and vertical and horizontal gradients of density while developing estimates for the subduction rate.

The NCAR Climate System model is being run in collaboration with scientists at NCAR in both global (at NCAR) and Atlantic basin (at WHOI) configurations. Equilibrium fields have been calculated for annual repeat forcing. The model is currently being spun-up with daily forcing for the 10 year period preceding the subduction experiment, with calculations extending through the subduction period to follow immediately after. The high resolution frontal instability calculations have been used as a benchmark for the evaluation of eddy flux parameterization schemes in a simple two dimensional model (Visbeck *et al*., 1997). The Semi-Spectral Primitive Equation Model (SPEM) has been configured in regional and periodic domains to study the influences of large scale deformation fields on the formation and maintenance of upper ocean fronts. Adiabatic and buoyancy forced calculations have been carried out, and scaling theory for the amplitude of the ageostrophic circulation has been developed. The Miami Isopycnal Coordinate Ocean Model (MICOM) has been configured to study eddy formation and spreading processes by the Labrador Current in the vicinity of the Flemish Cap.

RESULTS

The Azores-Bermuda high pressure cell was shifted more to the northwest relative to climatology, with the result that northeast trades dominated the area and westerly winds were found only in the northwest corner of the domain. The pattern of the curl of the wind stress had somewhat larger scales and smaller amplitude than anticipated, but the current meter data shows that the array spanned a region of convergent flow in the mixed layer. The annual cycle in surface fluxes yielded an annual cycle in upper ocean structure that varied across the array; the surface heating had larger amplitude peaks during the winter and summer at the northern side of the array, so that winter mixed layers were deeper and summer mixed layers shallower there. Non-locally forced variability with periods of weeks was evident in the thermocline and superimposed on the annual cycle. Strong near-inertial and baroclinic tidal motion was evident in the thermocline across the array. Closure of the local heat budgets at each of the five moorings shows that significant exportation of heat is needed at the central mooring beyond the vertical mixing processes built into PWP, while the four perimeter sites are much closer to being successfully described as one-dimensional. This is consistent with a maximum in Ekman pumping near the center of the array, and work continues to map the various terms, including Ekman pumping, that contribute to subduction.

The cross-front exchange of mass and release of potential energy resulting from baroclinic instability of the front has been accurately reproduced in a two-dimensional model with space and time dependent mixing coefficients that are derived from the properties of the large scale flow (Visbeck *et* al., 1997). This approach combines elements of the Gent and McWilliams and the Stone methodologies. Horizontal deformation fields (as provided, for example, by mesoscale eddies) are shown to produce mixed layer fronts consistent with those observed during the Frontal Air-Sea Interaction Experiment (FASINEX) (Spall, 1997). The ageostrophic horizontal and vertical motions and vertical heat fluxes are consistent with that expected from scaling theory and found in FASINEX. The deformation field responsible for the frontal formations has been shown to stabilize the front relative to the spin-down case. Nonlinear equilibration between the large scale deformation field and baroclinic instability of the sharp front is achieved. Time-dependent, large amplitude, meandering fronts are produced that remain as coherent, sharp frontal regions for many instability cycles. The result differs from the unforced, periodic channel frontal calculations in which the front breaks down over a few instability cycles, but is consistent with the observations of long-lived fronts in FASINEX. The Labrador Current was shown to be baroclinically unstable where it flows along the topography near Flemish Cap. Large amplitude meanders shed anti-cyclonic (low potential vorticity) eddies approximately 30-50 km in diameter with the density and water properties of upper Labrador Current Water. These eddies are entrained into the offshore barotropic deep Labrador Current near the northern edge of the Flemish Cap, where topography abruptly turns towards the south, and are carried into deep water on the offshore side of Flemish Cap. The model results are consistent with recent observations of sub-mesoscale eddies of upper Labrador Sea Water found embedded in the deep Labrador Current. One-dimensional mixed layer model results suggest that under severe winter conditions Labrador Sea Water can be directly ventilated in the Deep Western Boundary Current System, resulting in rapid subduction and advection to the south (Pickart *et al*., 1997).

IMPACTS/APPLICATIONS

Two years of high quality surface meteorological and oceanographic data from a large scale array of surface moorings in the eastern North Atlantic are providing the basis for evaluation of the accuracy of gridded model fields of surface forcing. The accompanying oceanographic data will extend our understanding of upper ocean response over seasonal time scales. Together, the meteorological and oceanographic data sets will allow examination of the coupling of the directly-forced surface layer of the ocean to the interior.

A common theme to each of several of the modeling studies is improving our understanding of frontal dynamics and the role of fronts in the general circulation. The results relating to how water is exchanged and subducted at both open ocean fronts (FASINEX) and near coastal fronts (Labrador Current) give insight into how fronts act as controlling factors in the exchange of water masses between different flow regimes. Understanding and representing the details of frontal instabilities, and the resulting eddy formation and propagation, are essential to the development of high resolution regional models. It has also been found here that even weak horizontal deformation fields can drastically alter the stability characteristics of strong frontal regions. Such frontogenesis mechanisms must be properly represented if one is to accurately predict frontal formation or evolution on time scales of days to years. Finally, a fundamental understanding of the physics that govern cross-frontal exchange processes is key to parameterizing their influences in non-eddy resolving general circulation models.

TRANSITIONS

Surface meteorological data was telemetered via satellite and after recovery made available to forecast centers. The Subduction data are being used to investigate the quality of the surface fields from recent reanalysis projects by the forecast centers. They are also being used by Josey and Taylor at Southampton Oceanography Centre (SOC) in the U.K. to confirm the improvements in their new, more accurate revision of the ship report-based surface meteorological and air-sea flux fields.

RELATED PROJECTS

This effort is one of a related set of projects that are part of the Subduction Experiment. In addition, the Subduction Central mooring carried instrumentation deployed in support of the North Atlantic Tracer Release Experiment (NATRE).

The frontal processes studied here are relevant to a number of other ONR, NSF and NOAA programs. The cross front exchange mechanisms, both open ocean and the Labrador Current over topography, are relevant to the ONR funded PRIMER experiment on shelf-break front processes. The formation of Labrador Sea water eddies by the Labrador Current is also relevant for the NOAA Atlantic Climate Change Program (ACCP), the NOAA/NSF Atlantic Circulation and Climate Experiment (ACCE), and the ONR subpolar ARI. The development of parameterizations for eddy fluxes in low resolution models is important for basin-scale models of the general circulation.

REFERENCES

Moyer, K. A. and R. A. Weller, 1997. Observations of surface forcing from the Subduction experiment: A comparison with global model products and climatological data sets. Journal of Climate, in press.

Pickart, R. S., M. A. Spall, and J. Lazier, 1997. Mid-depth ventilation in the western boundary current system of the subpolar gyre. Deep-Sea Res., 44, 1025-1054.

Spall, M. A., 1997. Baroclinic jets in confluent flow. J. Phys. Oceanogr., 27, 1054-1071.

Visbeck, M, J. C. Marshall, T. Haine, M. A. Spall, 1997. On the specification of eddy transfer coefficients in coarse resolution ocean circulation models. J. Phys. Oceanogr., 27, 381-402.

http://uop.whoi.edu/ (WHOI Upper Ocean Processes Group home page)